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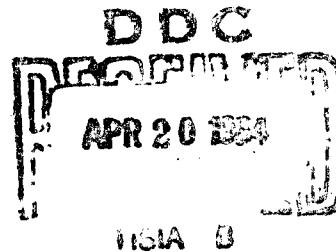


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**CELL EQUALIZATION TECHNIQUES**  
**Contract No. AF 33(615)-1342**  
**QUARTERLY TECHNICAL PROGRESS REPORT**  
**1 January 1964 to 1 March 1964**

**Prepared by**

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## FOREWORD

This report was prepared by P. R. Mallory & Co. Inc., Indianapolis, Indiana for Aeronautical Systems Division of Wright-Patterson Air Force Base, Ohio, on Contract Number AF 33(615)-1342, Task 817304-18.

It is our pleasure to acknowledge the assistance of Mr. W. S. Bishop of the Aeronautical Systems Division, who is the project engineer.

The work covered by this report was accomplished under Air Force Contract No. AF 33(615)-1342, but is being published and distributed prior to Air Force review. The publication of this report, therefore, does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

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## ABSTRACT

There are two modes of operation for a stabistor charge control circuit 1) thermal coupling the stabistor to the cell and 2) thermal isolation of the stabistor from the cell. Thermal coupling has been demonstrated in circuits BCC-2 and BCC-3, where the former cycled for 2700 cycles and the latter for 785 times. Thermal isolating is being demonstrated in circuit BCC-4 which has, as of this writing, cycled over 400 times.

Preliminary investigations indicate that a germanium power transistor may be used more effectively as an antireversal diode than the germanium diode now being used.

Attempts to fabricate a backward diode were fruitless; it is very difficult to fabricate a device with backward diode characteristics across a large area junction.

## I. Introduction

The first phase of the investigation into "Cell Equalization Techniques" was completed with the publication of TDR #63-4187. In this exploratory study, it was found that the life of alkaline cells could be extended by stabistor charge control. Specifically, one experimental charge control circuit has been cycled in excess of 2700 times and a second charge control circuit 785 times without catastrophic failure of cells or semiconductors. The new contract marks the beginning of the subsequent phase, that is extensive testing of stabistor charge control circuits using hermetically sealed cells.

The concept of utilizing the forward characteristic of a semiconductor diode for cell charge control demanded an amalgam of two diverse and difficult technologies (battery and semiconductor). The initial effort then had of necessity to encompass a very broad area which within the time limits of the contract period could permit of only a general attack on the overall problem although some areas were treated fairly intensively.

The cell was treated as a two-terminal black box with an upper voltage limit which should not be exceeded. The protecting stabistors were designed simply from the point of view of current handling capability and forward voltage drop as were the anti-reversal diodes. Stabistor assemblies were constructed and placed across the cells and the test cycles launched.

While initial results proved promising, they also pointed up the need for more fundamental information, both theoretical and practical, if a definite program was to be established. A good portion of this quarter was spent largely in accumulating background data through consultation and communication with the engineering groups of Inland Testing and of several cell manufacturers, through literature research and interlab communication.

As a result of this effort, the essential problem of stabistor charge control particularly as regards Ni-Cd cells can be defined more clearly. Ideally, stabistors should draw no current until the hydrogen voltage

potential is reached at which point they should exhibit zero dynamic impedance. Practically, however, they always draw some current during the charge cycle due to leakage currents, and at end of charge do not carry the full charging current.

This program will consider the cell, stabistor and anti-reversal diode as an integral unit. A strong emphasis will be placed on the determination of cell charging--discharging characteristics not only for Ni-Cd but also of Ag-Zn and Ag-Cd cells with a view to using this data in stabistor design. Consideration will be given also to thermal coupling and thermal isolation of stabistor to cell. However, most of the time under this contract will be used chiefly in exhaustive cycle testing of stabistor controlled series connected cells over a wide range of operating conditions.

The P. R. Mallory Company submitted to Aeronautical Systems Division a proposal entitled "Cell Equalization and Anti-Cell Reversal Techniques for Secondary Batteries" in response to Purchase Request No. 127425 and as a result was awarded Contract AF 33 (615)-1342, effective 1 January 1964 and terminating 31 December 1964. The objective of this program is to continue investigating methods of equalizing the terminal voltage of individual secondary cells in a series connected group. Another objective is to investigate methods of preventing cell reversal upon discharge. The work program will include, but will not be limited to, theoretical and experimental determination of a reliable method of cell equalization on charge and elimination of cell reversal on discharge. It will also include extensive cycling of hermetically sealed cells. Two experimental sets including batteries shall be delivered.

## II. Discussion and Factual Data

### A. Reduction of Stabistor Leakage Current During Open Circuit Stand

One of the limitations of stabistor charge control is that the

stabistor draws an appreciable amount of current from the cell during open circuit stand. This current amounts to as much as  $c/20$  and will completely discharge the cell in time. This leakage current is due to the stabistor and not the germanium diode since the leakage of the latter is only approximately 0.4 milliamperes.

This undesirable leakage current may be decreased by decreasing the resistivity of the silicon in the depletion region. This reduction in leakage current will be at the expense of forward voltage drop and dynamic impedance. In other words, if the stabistors are to operate properly, they must have some leakage current.

There are three possible methods of reducing the resistivity in the depletion region 1) decreasing the diffusion depth, 2) using lower resistivity material and 3) fabricating an alloyed junction instead of a diffused junction. Decreasing the diffusion depth by lowering the diffusion time on .005 ohm-cm material resulted in no significant decrease in leakage current. This investigation will be continued using lower resistivity material (.002 ohm-cm) and some alloyed junctions will be prepared.

#### B. Power Transistors as Anti-reversal Diodes

Investigations on the possibility of using a germanium power transistor as an anti-reversal diode have been completed. The results indicate that a power transistor may indeed be used to replace a germanium diode in this application. The advantages of using a germanium power transistor are as follows: 1) tested quality and reliability, 2) better current handling capabilities and 3) lower cost.

Six types of germanium power transistors have been evaluated. The forward voltage drop at 20 and 30 amperes for these devices are tabulated in Table 1. The forward drops of the best anti-reversal diodes available are included. A 2N630 having the lowest forward voltage drop will be used.

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Six types of germanium power transistors have been evaluated. The forward voltage drop at 20 and 30 amperes for these devices are tabulated in Table 1. The forward drops of the best anti-reversal diodes available are included. A 2N630 having the lowest forward voltage drop will be used.

### C. Backward Diode Fabrication

Attempts were made during this period to fabricate a composite device which would replace both the stabistor and anti-reversal diode and also have better anti-reversal protection, i.e. 0.2 volts. Such a device is a backward diode and has a silicon p-n junction depletion region of 50-200 Å. The reverse voltage breakdown of this device can be as low as 0.1 volts because of the current generated by internal field emission. If the depletion region is greater than 200 Å the reverse voltage breakdown increases to zener breakdowns. Still larger depletion regions result in avalanche breakdowns. So the criteria used to determine how nearly a backward diode is formed is to measure the reverse voltage breakdown, and the lower the breakdown, the closer the device is to being a backward diode.

The technique used to fabricate such a device is to have a nearly perfect step junction of very low resistivity. The procedure used was to vacuum evaporate aluminum on chemically polished damage free silicon slice (.0005 - .0008 ohm-cm) and flash alloy (1 minute at 1000°C) the aluminum then quench to minimize the diffusion of aluminum into the silicon. The alloyed slice was then scribed .050" x .050" and tested.

Preliminary experiments indicated that vacuum evaporating aluminum on a cold substrate slice resulted in poor aluminum adhesion. To correct this condition, the aluminum was evaporated on a substrate slice at 500°C.

This process yielded 3, 4 and 5 volt reverse breakdowns (zener mechanism). Any attempt made to decrease the junction depletion region (decrease voltage breakdown) by lowering of the temperature or time resulted in reverse breakdowns being shorts. Actually this is ideal except the forwards were shorts also. This author feels that the reason for this

gap (0 to 3 volts) is that the area of the p-n junction is too large, that is statistically it would be difficult to make a p-n junction having backward diode characteristics (depletion region of 50 to 200 Å) across a large area (.050" x .050"). The literature does report a silicon backward diode but the junction area is 250 times smaller (.003" x .003") and no mention is made of yield.

It is recommended that further work on this device be abandoned for the present time and if it is to be continued the N-type substrate should be phosphorous diffused before vacuum evaporating to decrease the resistivity.

### III. Equalization of Nickel-Cadmium Cells

#### A. Thermal Effects

There are two useful modes of operation for a stabistor charge control circuit 1) thermal coupling the stabistor to the cell, and 2) thermal isolation of the stabistor from the cell. Thermal coupling has been demonstrated in circuits BCC-2 and BCC-3, where the former cycled for 2700 times and the latter for 785 times without catastrophic failure of cells or semiconductors. The percent charge current bypassed by the stabistor and stabistor temperature rise at end of charge was 30% and 10°C above ambient, respectively.

Thermal isolation has been demonstrated in BCC-4 where two 4 AH Ni-Cd cells have cycled in excess of 400 times. The significance of thermal isolation is that the stabistor operates at a higher temperature at end of charge (approximately 40°C above ambient) and is capable of bypassing a greater percent (approximately 70%) of the charge current at end of charge. This stabistor current at end of charge may be made to be as much as 90% by using a smaller heat sink or a larger area stabistor. This stabistor configuration is particularly applicable to the equalization

of Ag-Cd and Ag-Zn systems where these cells can only tolerate an end of charge current of c/100 compared to c/10 for Ni-Cd cells.

#### B. Thermal Isolation Results

A new stabistor charge control circuit was designed for 4 AH nickel-cadmium cells. In this novel system, the stabistor and heat sink are thermally isolated from the cell. This configuration permits the manipulation of heat dissipation and allows the stabistor to operate at a higher temperature (approximately 40°C above ambient). The stabistor, having a negative voltage temperature coefficient draws more overcharge current at this higher temperature, and operating in this manner conducts as much as 70% of the end of charge current. Thermal coupling of the stabistor to cell on the other hand results in a lower temperature (approximately 10°C above ambient) since the cell has a high heat capacity. Consequently, the stabistor conducts only 30% of the charge current at end of charge.

This new charging circuit was constructed, having the stabistor and anti-reversal diode bolted to a 2" x 2" x 1/4" aluminum plate and thermally isolated from 2 Gould 4 AH nickel-cadmium cells in series. The system was cycled using a 55-minute charge--35-minute discharge to a depth of 75% (based on 4 AH). The charge and discharge currents were set at 5.1 amperes.

After successfully cycling the two Gould 4 AH cells (#3 and #4) for 297 cycles, two Burgess 4 AH cells (#1 and #2) were added to the series string. These cells were also isolated from the stabistor having the same arrangement and hardware as the Gould cells. At this point, the capacity of the cells was determined at a 35/60 hour rate (a constant 5.1 amperes discharge). The capacity to a 1.0 volt end point of cells #1, #2, #3 and #4 was 3.1, 3.4, 3.4 and 3.6 ampere-hours, respectively; to a 0.0 volt end point the capacity was 3.4, 3.6, 3.6 and 3.7 ampere-hours,

respectively. This four cell battery was then cycled at a charge and discharge current of 5.1 amperes. To date cells #3 and 4 have cycled 408 times and cells #1 and #2 cycled 111 times; the 14th cycle data for cells #1 and #2 and 311th cycle data for cells #3 and #4 are shown on Table 2.

It should be pointed out that since the depth of discharge was based on 4 ampere-hours and the capacity at a 35/60 hour rate for all the cells is less than 4 ampere-hours, then the cells were actually being subjected to a depth of discharge of greater than 75%. The actual depth of discharge for cells #1, 2, 3 and 4 based on their respective capacities is 97%, 88%, 88% and 83%.

#### C. Conclusions

1. A stabistor can be made to draw approximately 90% of the end of charge current by thermally isolating the stabistor from the cell. Bypassing a large percent of the end of charge current is particularly useful in silver-cadmium and silver-zinc systems where the tolerable end of charge current is c/100.
2. The capacity of a cell should be determined based on a 35/60 hour rate and not a 1 hour rate since the former rate is used in the cycling schedule.

#### IV. Program for Next Interval

1. Extensive charge and discharge testing will commence on hermetically sealed 4, 12 and 20 nickel-cadmium cells and 3, 12 and 20 silver-cadmium cells. These cells have been ordered from three different cell manufacturers and are due to arrive shortly.
2. The silver-zinc system will be investigated.
3. The four cell battery system now on test will continue to be cycled and test data taken.

TABLE 1

Forward Voltage Drops at 20 Amperes and 30 Amperes of  
Various Power Transistors Used as Anti-Reversal Diodes

Type	Vf (volts) at 20 amps	at 30 amps
1. 2N350A	.61	.71
2. 2N350A	.79	.9
3. 2N176	.64	.79
4. 2N176	.90	1.02
5. 2N554	.62	.70
6. 2N554	.62	.70
7. 2N630	.45	.52
8. 2N630	.50	.55
9. 2N2152	.92	1.19
10. 2N1162	.6	.73
11. Germanium Diode	.55	.62
12. Germanium Diode	.55	.62

Table 2

14th Cycle Data for Burgess Cells #1 and #2 and 311th Cycle Data for Gould Cells  
 #3 and #4 in Circuit BCC-4 at 29°C. Charge and Discharge Current-5.1 Amperes

Time (min.)	Stabilistor Current (amp)	Cell Voltage (volts)				Stabilistor Temp. (°C)							
		I <sub>1</sub>	I <sub>2</sub>	I <sub>3</sub>	I <sub>4</sub>	V <sub>1</sub>	V <sub>2</sub>	V <sub>3</sub>	V <sub>4</sub>	T <sub>1</sub>	T <sub>2</sub>	T <sub>3</sub>	T <sub>4</sub>
1	.14	.12	.13	.12	.12	1.38	1.38	1.39	1.39	32	35	29	29
15	.70	.72	1.36	1.24	1.46	1.47	1.50	1.50	1.50	37	38	30	31
31	1.46	1.35	1.96	1.90	1.49	1.49	1.51	1.52	1.52	42	43	42	44
43	3.00	2.36	2.60	2.70	1.50	1.50	1.51	1.52	1.52	53	51	53	55
53	4.15	2.90	3.25	3.40	1.47	1.48	1.51	1.52	1.52	69	59	61	64
Discharge	3	.19	.11	.14	.14	1.28	1.28	1.32	1.31	57	51	48	49
15	.03	.02	.04	.03	.03	1.22	1.22	1.27	1.26	36	39	33	33
27	.02	.01	.02	.02	.02	1.19	1.18	1.23	1.23	32	36	30	30
34	.01	.01	.01	.01	.01	1.12	1.07	1.17	1.17	32	35	29	29